MEASUREMENTS OF BEAM-BEAM KICK USING A GATED BEAM-POSITION MONITOR UNDER CRABBING COLLISION AT KEKB

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Abstract

KEKB provides facilities to realize an effective head-on collision by using of crab cavities through crossing collision and to obtain an improved specific luminosity. A gated beam-position monitor (GBPM) that is capable of measuring the beam phase and transverse position of a specific bunch in a bunch train has been developed. This GBPM is used to measure a beam-beam kick. The monitor estimated the effective horizontal beam size at an interaction point (IP) from a linear part of the beam-beam kick and revealed the effect of the crab cavities on the beam-beam kick. According to the dynamic beam-beam effect, the estimated horizontal beam size is in good agreement with the calculated beam size.

INTRODUCTION

KEKB [1] is a multi-bunch, high-current, electron/positron collider for *B* meson physics. The collider consists of two storage rings: a low energy ring (LER) for a 3.5-GeV positron beam and a high energy ring (HER) for 8-GeV electrons, respectively. Both the rings can store more than 1500 bunches, where the harmonic number is 5120 with an RF frequency of 509 MHz. The bunches are stored in two rings with a 3-bucket (6 ns) or 4-bucket (8 ns) spacing, forming a single bunch train followed by empty buckets that occupy approximately 5% of the circumference. Additional bunches, called pilot bunches, are placed just after the train, at different locations in each ring so that they do not collide with each other.

The two beams collide at one interaction point (IP) with a horizontal crossing angle of 22 mrad. Crab cavities that were installed in 2007 can provide horizontal tilt to a bunch without changing the central orbit using a dipole-mode kick operating at the RF frequency [2]. The crab cavities enabled the realization of an effective head-on collision at the IP. Crabbing collisions are successfully performed for the first time and they lead to an increase in a specific luminosity [3]. Since only one crab cavity is installed per ring, the effect of the crab kick can be observed in the entire ring.

GATED BEAM-POSITION MONITOR

A gated beam-position monitor (GBPM) uses a fast switch for selecting a specific bunch that is attached to a turn-by-turn BPM [4] and measures the beam position of individual bunches. One of the functions of the GBPM is to measure the beam-beam effect by comparing the beam parameters of a colliding bunch with those of the non-colliding pilot bunch. Signal processing is performed within a revolution period. This gated measurement has the following features:

- The position measurement is not affected by a global orbit correction.
- Any imbalance in the gain of the detector is cancelled out by subtraction.
- However, the measurement is not simultaneous.
- Errors are increased when the intensity between bunches to be measured is largely unbalanced.

Figure 1 shows the schematic diagram of a GBPM. Button type electrodes are mounted with a cylindrical vacuum pipe with a diameter of 64 mm to pick up a beam pulse. The system can select an electron or a positron bunch and it employs a common detector. A Bessel type low-pass filter with a cut-off frequency of 1.5 GHz is attached to a gate module so that the high frequency components of a button signal would be eliminated. The gate selects a specific bunch in a bunch train with a pulse width of 8 ns: a commercially available switch (Hittite-HMC234C8) is used as the gate. Through in-phase and quadrature phase (IQ) detection at an acceleration frequency of 509 MHz, the monitor can obtain a longitudinal position or the beam phase of a bunch as well as the transverse beam positions of a specific bunch. Two orthogonal signals are fed into 8-channel ADCs with a resolution of 12 bits. The peak of a detected pulse with a width of 20 ns is sampled in the ADCs at a revolution frequency of 100 kHz. The sampled data are stored successively in a memory.

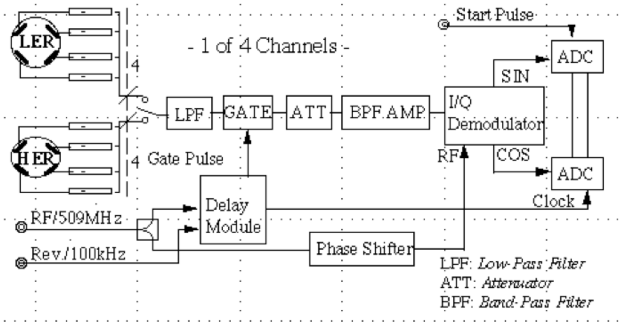

Figure 1: Schematic diagram of a gated beam-position monitor system.

The on/off isolation of the gate module was tested for a bench. An isolation of more than 50 dB at 2 GHz is obtained: two series of the switches are used to increase the isolation. The isolation of the system was also measured using real bunches placed with a spacing of 8 ns (4 buckets), while shifting the timing for the gate and for the clock of the ADCs in the unit of bucket. The isolation of the beam intensity was approximately 40 dB for a 3-bucket spacing. The degradation in the isolation would be due to a long tail of a pulse signal. Although the system can measure successive beam positions, the beam position data are averaged over 2,000 turns for determining the closed orbit. The standard deviation of the averaged position measurement is 3 to 5 μm and the resolution of the phase is 0.10°. The performance of the GBPM is summarized in Table 1.

Table 1: Specifications of GBPM

Pick-up Electrode	Button
Detector Bandwidth	509 ± 30 MHz
Position Resolution	20 μm at turn-by-turn 3 to 5 μm at average
Phase Resolution	0.3° at turn-by-turn 0.10° at average
Gate Isolation	> 50 dB at 2GHz 40 dB at 6 ns spacing

BEAM-BEAM KICK

When two beams collide with an orbit offset, Δ^{*}_{x} at the IP, bunches are kicked by an electromagnetic force of the opposite beam and the orbits of both beams are distorted around the ring. A position monitor located at a phase advance of $\Delta\varphi_d$ from the IP detects a position shift due to the collision. A position shift at a detector is given by

$$\Delta X_{\mathrm{det.}} = \frac{\sqrt{\beta_{\mathrm{det}}.\beta^{*}}}{2\,sin(\pi\nu)}\theta_{bb}\cos(\pi\nu - |\Delta\varphi_d|). \qquad (1)$$

Here, $\beta_{\mathrm{det.}}$ and β^{*} are the beta functions at the detector and the IP, respectively and ν is the betatron tune and θ_{bb} is the beam-beam kick angle. Assuming that the vertical offset is zero, the horizontal beam-beam kick θ_{bb} is expressed using the following rigid Gaussian model as

$$\theta_{bb} = \frac{-2r_e N_b}{\gamma}\Delta^{*}_{x}\int_0^{\infty}\frac{\exp(-\frac{\Delta^{*2}_{x}}{(t+2\Sigma_x^2)})}{(t+2\Sigma_x^2)^{3/2}(t+2\Sigma_y^2)^{1/2}}dt, \qquad (2)$$

where, Σ_x and Σ_y are the effective horizontal and vertical beam sizes, respectively, r_e is the classical electron radius, γ is the relativistic factor, and N is the number of particles in a bunch. The effective beam size is defined by $\Sigma_{x/y} = \sqrt{(\sigma^{+}_{x/y})^2 + (\sigma^{-}_{x/y})^2}$. The superscript ± denotes positron or electron bunches. The beta function dynamically changes according to the beam-beam parameter, depending on the betatron tune. A calculation using the optics parameters shows that the product of the beta functions is constant, i.e., $\sqrt{\beta_{\mathrm{det}}\beta^{*}} \approx 4.0\,\mathrm{m}$. Thus, the position shift at the detector position is proportional to the beam-beam kick. When the horizontal offset is smaller than the beam size, Eq. (2) is approximately expressed as follows:

$$\theta^{\pm}_{bb} \approx \frac{-1.94 r_e N^{\mp}}{\gamma^{\pm}}\frac{\Delta x^{*}}{\Sigma_x^2}. \qquad (3)$$

By using Eq. (3), we can estimate the effective horizontal beam size at the IP from the slope $\theta^{\pm}_{bb}/\Delta x^{*}$.

Since the analytical formula in Eq. (2) is based on the head-on collision, a different configuration is required to calculate a beam-beam kick with a crossing angle. Figure 2 illustrates the calculation of the beam-beam kick for a collision with a crossing angle of 22 mrad. Further, it is assumed that a single particle collides with a rigid Gaussian bunch. A particle is horizontally moved with the crossing angle. Each set of kick data are summed up, according to the longitudinal beam profile of the bunch. Figure 3 shows a comparison of two beam-beam kicks of particles with and without the crossing angle for the same bunch intensity. By transforming the collision scheme from the crossing collision to the head-on collision, the beam-beam kick increases and the estimated effective beam size decreases. Since the slope in a head-on collision around the linear part is roughly twice that in a crossing collision, it is estimated that the relative beam size is reduced by a factor of 1.4 in a crabbing collision.

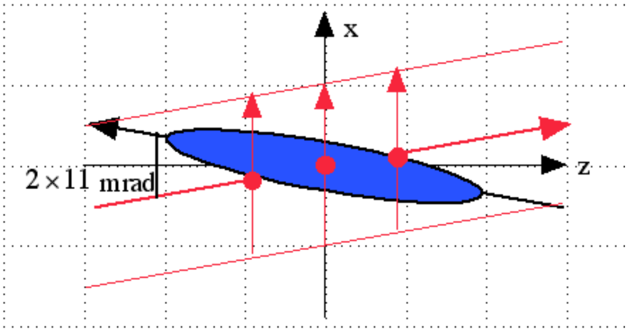

Figure 2: Schematics for calculating the beam-beam kick of a particle for a crossing angle of 22 mrad. Co-ordinates "x" and 'z" represent the horizontal and longitudinal directions, respectively. A particle moves in the horizontal direction with a slope of 22 mrad for a bunch.

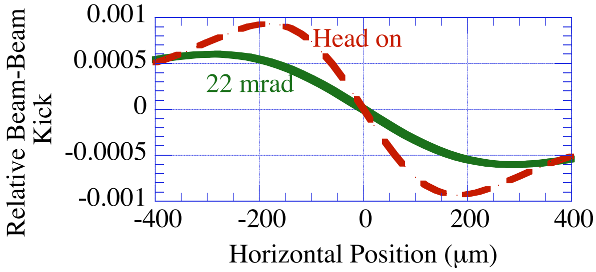

Figure 3: Relative beam-beam kick as a function of the horizontal position; the dashed red line indicates the relative beam-beam kick with head-on collision and the solid green line indicates that with a horizontal crossing angle of 22 mrad under the same beam conditions.

MEASUREMENTS

Beam-beam Kick

Although the tilt of a bunch profile resulting from crab cavities is directly observed by using a streak camera [5], its effect can be estimated by measuring the beam-beam kick at the IP. The GBPM compares a position between the colliding and the non-colliding bunches, when the relative orbit between the electron and the positron beams at the IP is varied. After the careful tuning of the crab voltage and the phase, the scanning of the horizontal orbit was performed at the IP. Figure 4 shows the position shift with and without the crab cavity as a function of the setting value of the horizontal offset. It was confirmed that the horizontal offset was in good agreement with the actual orbit displacement at the IP within 10%. Both data were taken under almost the same beam conditions except for the crab voltage. There is a clear difference in the slope around the zero offset between the two conditions. The effective horizontal beam size estimated using Eq. (3) is $\Sigma_x = 167 \pm 3$ μm with the crab voltage and $\Sigma_x = 230 \pm 3$μm without the crab voltage. The effective horizontal size at the IP reduced to 72 % in the crabbing collision. This measured value is consistent with the calculation. A decrease in the horizontal beam size could contribute to an increase in the luminosity. Since the crab cavity is very effective, the operations are performed for crabbing collision. The effective beam size was measured in the usual operations. The measured size was smaller than a size calculated without the collision as shown in Fig. 5. Since the horizontal betatron tune is close to a half-integer, the dynamic beam-beam effect greatly contributes to the beam size. Figure 5 shows that the dynamic effect for betatron tunes of 0.51 or 0.54 can explain the measured beam size.

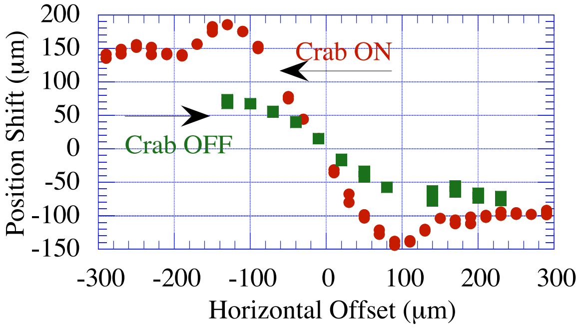

Figure 4: The position shift of a positron bunch detected at the monitor as a function of the horizontal orbit offset: the red dots indicate the position shifts that are measured for a crabbing collision and the green squares indicate that without the crab voltage. The positron and electron bunch currents measured with a crab voltage are 0.64 and 0.47 mA with the crab, while those without the crab voltage are 0.73 and 0.42 mA, respectively.

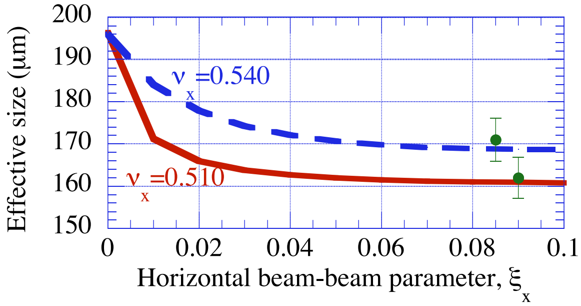

Figure 5: Measured effective horizontal beam size indicated with green dots as a function of the beam-beam parameter. The beam-beam parameter was estimated from a coherent beam-beam tune shift. The calculated beam sizes are shown for the case of two fractional tunes: 0.510 (solid red line) and 0.540 (blue dashed line).

DISCUSSION

The beam-beam kick angle can be obtained from the position shift data using the optics parameters. A measured beam-beam kick is represented along with the calculated kicks as shown in Fig. 6. When we assume a rigid Gaussian bunch with an effective size of 162 μm, the measured kick agrees well with the calculated kick around the center. However, the measured kick deviates from the calculated kick curve, when the horizontal offset is larger than approximately 100 μm. The measured kick is smaller than the calculated one when the size is greater than 196 μm. The result suggests that the beam density in the peripheral region of a bunch profile decreases and slightly expands, although the density in the central part increases due to the dynamic beam-beam effect. The distorted horizontal profile might be related to the lifetime limitation observed at a high beam-beam parameter.

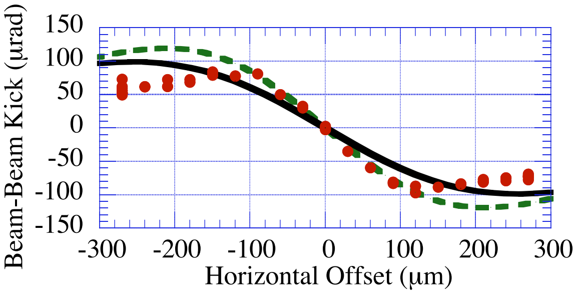

Figure 6: Measured (red dots) and calculated (dashed green and solid black) beam-beam kicks as a function of the horizontal offset. The dashed green line indicates kicks with an effective size of 162 μm and the solid black indicates kicks with a size of 196 μm: the calculated kicks are for a Gaussian profile.

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